# A NEW EROSION CYCLE IN THE GRAND CANYON DISTRICT, ARIZONA

H. H. ROBINSON

## INTRODUCTION

The Grand Canyon District of Arizona possesses a particular interest for the geologist in that its history, at least from the beginning of the Tertiary, must be interpreted almost entirely from physiographic data; that is to say, the region has been subject to erosion for so long a period that stratigraphic evidence is lacking. The absence of such evidence, which long usage has fixed as the conventional means of interpreting geologic history, may have caused, perhaps, some doubt to be felt as to the reality of the conclusions originally reached by Dutton in 1882 in regard to the history of the region, for at that time the data of physiography were in a more or less embryonic state and their interpretative value was hardly recognized. Indeed, Dutton's report on the Tertiary history of the Grand Canyon District[1] was a pioneer work in this branch of geology and its significance becomes increasingly apparent with the passage of time. Today conditions are changed, physiography has taken its place as a systematic science, and the relation between topographic forms and the conditions under which they may originate may be considered as resting on a reasonably broad and well-established foundation. Thus conclusions based upon physiographic evidence are now accepted as of equivalent value to those based on older and more conventional lines of evidence, where twenty-five years ago they were looked upon with skepticism by the majority of geologists who had not had a physiographic training. That there was good reason for this attitude is well illustrated by the new erosion cycle described in this article, for the facts upon which it is based have been known for twenty-five years without their significance being fully

[1] *Tertiary History of the Grand Canyon District, Arizona, with Atlas* (Monogr. II, U.S.G.S., 1882).

appreciated, thus indicating the recent nature of the growth of physiography from the descriptive to the broader interpretative stage.

## REVIEW OF FORMER WORK

It will assist in understanding the bearing of this new cycle of erosion on the Tertiary history of the region if a partial summary of some of the former work is first presented. The actual amount is, indeed, not great, considering the length of time the region has been known and its interest recognized; possibly the extent of the field and the evident inaccessibility of much of it have exercised a deterrent influence.

The nature of the plateau problem was clearly appreciated by Newberry who in 1858 was the second geologist to traverse the region. His route lead him along the southern side of the Grand Canyon, and the conclusion he reached from the character of that and other parts of the plateau was that erosion had been the predominant factor in producing the relief. The following quotation will give his point of view:

> . . . . Before returning to the details of the local geology of our route, I ought perhaps to refer briefly to two questions of general importance, which would naturally suggest themselves to any geologist who should traverse the table-lands west of the Rocky Mountains, or should receive an accurate description of them from others.
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> The first of these questions is: To what cause is due the peculiar topographic features of the surface of the table-lands—where different formations succeed each other in a series of steps, which generally present abrupt and wall-like edges—the more recent strata occupying the highest portion of the plateau?
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> The first question belongs appropriately to the subject of surface geology, and will be referred to again. I may say here, however, that, like the great canyons of the Colorado, the broad valleys bounded by high and perpendicular walls *belong to a vast system of erosion, and are wholly due to the action of water*. Probably nowhere in the world has the action of this agent produced results so surprising, both as regards their magnitude and their peculiar character.[1]

The first extended account of the region, however, did not appear until 1882 when Dutton's *Tertiary History of the Grand Canyon District* was published. The history of the region as

[1] *Report on the Colorado River of the West. Explored in 1857–1858, by Lieut. J. C. Ives*. Washington, 1861. Part III, Geological Report by J. S. Newberry, p. 45.

deciphered by Dutton, and omitting many details of an admittedly speculative character, comprised the following events:

1. A period of great denudation during which a thickness of strata averaging 10,000 feet was removed from over an area of 13,000 to 15,000 square miles. This period ended somewhere about the close of the Miocene.

The Grand Canyon platform then may have lain near sea-level, and the remnants of Mesozoic beds . . . . were gradually obliterated, and the entire region was planed down to a comparatively smooth surface [p. 119] . . . . and was at a base-level of erosion [p. 120].

2. A canyon-cutting cycle. This was initiated by an epoch of faulting at the beginning of the Pliocene which elevated the region from 2,000 to 3,000 feet above the level it occupied at the close of the period of the great denudation.

At the epoch when the cutting of the present Grand Canyon began, no doubt the region at large presented a very different aspect from the modern one. While the greater part of the denudation of the Mesozoic had been accomplished, there were some important remnants left which have been nearly or quite demolished in still more recent times [p. 223]. . . . . The uplifting forces suspended operations for a time, and the drainage system sought a new base-level. During this paroxysm of upheaval the outer gorge of the Grand Canyon was cut, the river corrading down to the level of the esplanade in the Kanab and Uinkaret divisions, but below that horizon in the Kaibab [p. 226]. . . . . The process of erosion during this second period of base-level was occupied in the only possible work under the circumstances, viz., sapping the newly formed cliffs of the canyon. The cliffs, thus attacked, receded away from the river, gradually developing the broad avenue of the outer chasm [p. 121]. . . . . We now come to the final upheaval which brought the region to its present condition. . . . . A new paroxysm of upheaval set in . . . . amounting probably from 3,000 to 4,000 feet. The narrow, inner gorge of the Toroweap was swiftly cut and it is in this respect a type of the lower depths of the entire canyon. . . . . The epoch at which this latest upheaval took place is no doubt a very recent one in the geologic calendar. It began most probably near the close of the Pliocene [p. 228].

The history of the region, as worked out by Dutton, may be tabulated as follows:

I. The period of great denudation lasting until the close of the Miocene.
II. Uplift by folding (?) and faulting at close of Miocene.
III. The canyon cycle of erosion.
  *a*) Cutting of outer gorge of Grand Canyon during the Pliocene.
  *b*) Uplift by faulting at close of Pliocene.
  *c*) Cutting of inner gorge of the canyon during the Quaternary.

Davis,[1] as the result of two trips through the region, advanced several pertinent arguments supporting the broad conclusion of Dutton that the Grand Canyon District had experienced two cycles of erosion separated by a period of pronounced uplift. In the absence of local fossiliferous evidence he designated the earlier period of the great denudation as the plateau cycle and the later one, in which the canyon cutting occurred, as the canyon cycle. Especially suggestive was his argument in favor of two cycles based on the relatively great retreat of the cliffs from the canyon on its north side as compared with the slight retreat of the upper walls of the canyon from the river, the correctness of which was later confirmed by independent evidence (*a*, p. 118). He pointed out that the esplanade of the Kanab and Uinkaret sections of the canyon was best explained as a structural feature and from a variety of considerations concluded "that while many partial cycles of erosion may have preceded the long pause during which the broad denudation of the plateaus was completed, only a single uplift and a single downcutting are recorded in the canyon" (*a*, p. 185). This conclusion has since been confirmed by Dr. L. F. Noble as the result of detailed field work in the canyon in the vicinity of Bass's camp.[2]

Of critical significance was the recognition by Davis of an important period of faulting during the plateau cycle of erosion distinctly separated from the later faulting at the beginning of the canyon cycle. Definite evidence was obtained that relief of at least 1,000 feet, due to this faulting, was obliterated during the plateau cycle and that by the end of that cycle the region in general had been reduced to a peneplain.

In speaking of the reduction of the region to a peneplain at the close of the period of great denudation, Davis says:

> It therefore seems legitimate to say that the peneplain, so far as one was developed at the close of the first cycle, lay in the Permian formation at some unknown height above the present plateau surface in the Kanab district; and that the Carboniferous platform as now exposed in the Kanab Plateau is a

[1] *a*) "An Excursion to the Grand Canyon of the Colorado," *Bull. Mus. Comp. Zoology, Harvard College*, XXXVIII, May, 1901; *b*) "An Excursion to the Plateau Province of Utah and Arizona," *ibid.*, XLII, June, 1903.

[2] Unpublished manuscript.

stripped and somewhat dissected plain [*a*, p. 139]. . . . . Since the uplift by which the canyon cycle was introduced, sufficient time has elapsed for an extensive removal of the weaker Permian strata from the plateau surface. . . . . Even the resistant upper Aubrey strata, revealed by the stripping of their Permian cover, early in the canyon cycle, have suffered a significant amount of dissection, as seems to be the case over much of the Kanab Plateau; but the dissection here is not so mature as that by which the higher Kaibab is characterized [*a*, p. 137].

The general conclusions reached by Huntington and Goldthwait, as the result of a study of the Toquerville District, Utah,[1] coincided with those of Davis outlined above, but as the work was of considerable detail they were able to present the problem with somewhat greater fulness than had previously been done. In particular they were able to show "that at the end of the interfault cycle of erosion (the period of great denudation) the whole country was physiographically mature or even old. Certain regions of soft strata, chiefly near the Colorado River, had been reduced very nearly to base-level forming the Mohave peneplain."

Evidence has been presented by the writer[2] showing that the region about the San Francisco Mountains,[3] south of the Grand Canyon, was also reduced to a peneplain which involved not only soft Permian and Triassic strata but also the highly resistant upper Aubrey cherty limestone. It was concluded from a study of the literature that the peneplain most probably covered the entire southern portion of the present Colorado Plateaus and extended, in the Bradshaw Mountains, into the Basin Range country of Arizona. The remnants of the peneplain are sufficiently numerous to make it certain that practically the entire Grand Canyon District was reduced to base-level at the close of the period

[1] "The Hurricane Fault in the Toquerville District, Utah," *Bull. Mus. Comp. Zoology, Harvard College*, XLII, February, 1904.

[2] "The Tertiary Peneplain of the Plateau District, and Adjacent Country, in Arizona and New Mexico," *Am. Jour. Sci.*, XXIV (August, 1907), 109–29.

[3] The term "San Francisco Mountains" is here used to designate a group of six large and several hundred small volcanoes and their associated lavas, which covers an area of some 2,000 square miles on the plateau south of the Grand Canyon. The group takes its name from San Francisco Mountain, the largest mountain volcano of the region.

of great denudation. The peneplain was developed over much of the region on the soft Permian and Triassic strata and owes its preservation to a capping of basalt. The extent of the peneplain and the fact that it is developed across the basset edges of strata varying in hardness from a compact sandstone to a barely consolidated marl, as at Black Point in the Little Colorado Valley and elsewhere, force the conclusion that a long period of time is represented, that the base of control was an oceanic body of water, and that consequently the region stood approximately at sea-level.

The history of the region, following Huntington and Goldthwait, may now be tabulated as follows:

I. Period of folding and flexing.
II. Erosion period.
III. The first faulting.
IV. Inter-fault cycle of erosion. Region reduced to a peneplain at close.
V. The later faulting.
VI. The post-fault canyon cycle of erosion.
Stripping of weak strata down to the upper Aubrey cherty limestone. Cutting of deep canyons. Refreshing of cliff profiles.

As bearing on what is to follow it may be noted that Davis, and also Huntington and Goldthwait, considered that the peneplain developed on the Permian and Triassic formations marked the close of the period of great denudation and that the stripping of these strata and the consequent exposure of the upper Aubrey limestone—the present surface rock of the region—occurred after the uplift which introduced the canyon cycle. Dutton also recognized the existence of a peneplain on Permian strata beneath the basalt cap of Mount Trumbull and at other localities (p. 224), and he also considered that the present surface of the plateau was likewise developed at a base-level of erosion (p. 118). He did not give these two planes of erosion distinct interpretative values, but used them as common evidence that the region stood at a low elevation at the close of the period of the great denudation. The proper discrimination between these two planes of erosion, as will appear in the sequel, gives the clue to an essential feature in the history of the Grand Canyon District which has not thus far been fully recognized.

THE ADDITIONAL EROSION CYCLE

The erosion cycle to which the remainder of this article will be largely devoted followed after the development of the extensive peneplain at the close of the period of great denudation but before the uplift which introduced the canyon cycle of erosion, and is to be associated with the former cycle rather than the latter. It was characterized by the widespread removal of a notable thickness of Permian and Triassic strata and the development of a thoroughly mature topography on the underlying resistant upper Aubrey cherty limestone—the present surface rock of the region. It will be called the post-peneplain cycle of erosion. The preceding cycle, which closed with the reduction of the region to a peneplain, will be designated as the peneplain cycle, while the latest cycle, as formerly, will be called the canyon cycle of erosion.

A striking feature of the Grand Canyon District, which impresses even the casual observer, is the pronounced contrast between the broad expanse of the smooth or but gently undulating surface of the plateau and the deep and precipitous walled canyons carrying the present drainage, a contrast that is highly suggestive of different conditions of origin.

In the region south of the canyon, with which the writer is particularly acquainted, the surface of the plateau is etched by an extensive system of shallow valleys of thoroughly mature form. They were first described by Newberry, in 1858, in the following terms:

> Where we crossed this divide it had the character of an elevated plateau, of which the surface has been considerably modified by erosion, and now presents many broad and shallow excavated valleys [p. 58].

Davis, in speaking of these valleys on the Coconino Plateau, says:

> . . . . We were much impressed with the maturity of their graded sides and floors, in contrast to the youthful expression of the precocious canyon. . . . . Furthermore, the contrast between the rapid wasting of the cliff in the canyon walls and the slow change of the mature valleys on the plateau strongly suggests that the processes represent different cycles of erosion [*a*, p. 120, and Fig. 2].

These old valleys are also well developed farther south in the vicinity of the San Francisco Mountains. Figs. 1 and 2 illustrate

the one which is located just southeast of Flagstaff. The perfect maturity of form which characterizes the small branches even to their very heads is well shown in Fig. 1. The slightly meandering course and mature side slopes of the main valley are seen in Fig. 2. The alluvial filling is suggestive of a well-graded condition of the stream, especially when taken in connection with the gently sloping sides. It is, however, a significant fact that the alluvium, which was deposited after the valley had acquired its

FIG. 1

mature form, extends to the head of the valley so that its deposition was independent of the grade.[1]

The region south of the canyon is, indeed, a network of these mature valleys, and it is to be presumed that the corresponding districts elsewhere are also covered with them. They occur on the Marble Platform, but have not been specifically described

[1] The same phenomenon is strikingly illustrated by the heavy alluvial mantles of the large volcanoes of the region which, on San Francisco Mountain, appear to be associated with glacial deposits. These alluvial deposits are now undergoing dissection, thus indicating a reversal of the conditions under which they were laid down.

as present on the Kanab Plateau. Apparently they are best preserved in those localities where they were developed on the upper Aubrey cherty limestone.

The valleys of the Kaibab (and also the Coconino) Plateau have been described by Davis as follows:

> The limestone [upper Aubrey] capping these plateaus is maturely dissected. Broad-floored, well-graded valleys with gently sloping sides ramify through the uplands in a most perfect manner, presenting a maturely developed form even to their heads; and this in spite of the fact that they are nearly always dry, for the wash of waste down their sides and along their floors is accomplished only during the rains and thaws of winter and occasional showers of summer [*a*, p. 120].

The above description embraces the valleys of the Coconino Plateau and also applies without alteration to the similar valleys farther south in the vicinity of the San Francisco Mountains. There is, therefore, little doubt, as will appear from later considerations, that all these valleys were developed in the same cycle of erosion. It may be noted, moreover, that, as these valleys had maturely developed form even to their heads, their lower courses must have originally possessed at least equal maturity of form, so that there is no doubt as to the thoroughly mature development of the topography throughout the Grand Canyon District during this cycle.

The post-peneplain cycle of erosion is separated from the preceding cycle of the great denudation, which closed with the widespread development of a peneplain, not only because of differences in topographic expression, but primarily because the mature topography occurs at a level distinctly below that at which the peneplain is found. This is a fact that is perfectly evident at many localities where structural complexities are absent. As, however, the peneplain involves a considerable thickness of strata ranging from the upper Aubrey (upper Carboniferous) limestone through Triassic formations, while the mature topography, so far as known, is developed, or at least preserved, only on the upper Aubrey limestone, the actual difference between the two planes of erosion is a variable one depending upon the thickness of Permian and Triassic strata that may be present at any locality.

In the vicinity of Flagstaff, close to the boundary between the upper Aubrey limestone and Moencopie (Permian) formation, the difference between the two planes of erosion is not over 200 feet. Along the eastern side of the Black Mesa, farther south, it ranges from 400 to 600 feet. At Cedar Ranch, 15 miles northerly from San Francisco Mountain, it has increased to 700 feet, while at Red Butte, nearer the canyon, it reaches a maximum of about 1,000 feet. Corresponding differences between the two planes of erosion

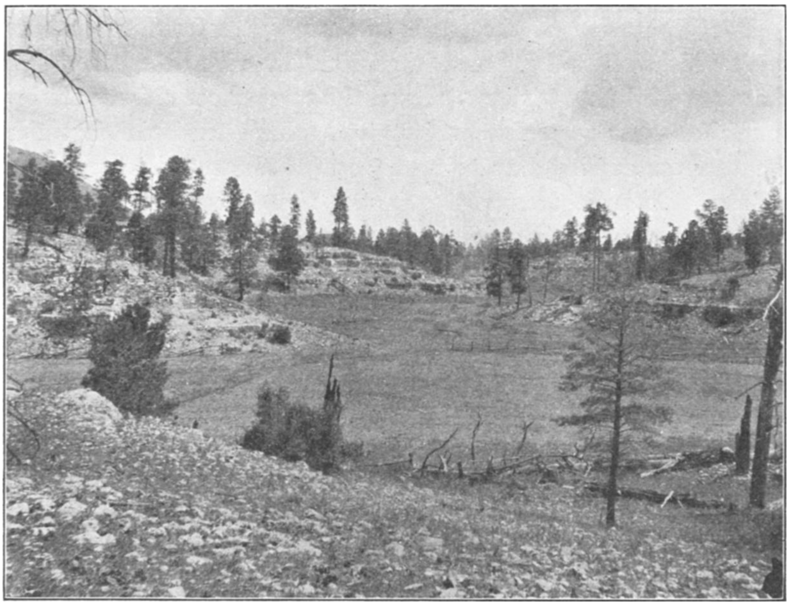

FIG. 2

occur on the north side of the canyon. In the southwest section of the plateau the difference is practically nothing, since the peneplain was developed on the upper Aubrey limestone and the forces of erosion, which were powerful enough to remove the in general weak Permian and Triassic strata elsewhere, had little effect on the resistant basalt capping the peneplain and on the underlying limestone. The only locality in the district which appears to have surely risen above the peneplain at the close of the period of the great denudation is the Kaibab Plateau. The surface

of this plateau is a stripped structural one formed by the upper Aubrey cherty limestone, and its elevation above the surrounding plateau country is due principally to monoclinal folding which occurred not later than the very beginning of the erosional history of the region in the Eocene. It must be supposed, then, that the surface of the Kaibab Plateau was reduced to maturity or old age, coincident with the development of the peneplain, and that its present mature topography represents a continuation of the process in the post-peneplain cycle of erosion.

The separation of the post-peneplain cycle from the canyon cycle which followed is based in part on the wide difference in the character of their drainage systems, the one perfect in its maturity, the other equally perfect in its youthfulness, and the fact that the canyon cutting has to some extent destroyed the mature valleys. There is abundant evidence that this latter process is still in progress; it is very plainly seen on both the north and south sides of the Kaibab section of the Grand Canyon where the older mature valleys are being consumed by the widening of the youthful canyon. Further, the courses of many of the partly consumed valleys lead away from the canyon, thus indicating that there has been such a radical readjustment of drainage lines in the canyon cycle as to bring about definite changes in their direction, and this is especially noticeable in the case of the trunk stream of the region—the Colorado River.

The tracing out of the mature valleys and reconstruction of the drainage system of the post-peneplain cycle of erosion is evidently an important problem which must be worked out before a satisfactory explanation for the location of the present canyon system of drainage can be offered. For the reconstruction of this mature drainage system should permit a definite idea of the attitude of the land during the post-peneplain cycle to be formed and consequently indicate the extent and magnitude of the regional warping which followed. Of equal importance, also, would be a study which would permit the reconstruction over an extensive area of the peneplain of the preceding cycle of erosion; this would assist in determining not only the extent of the warping but also the magnitude of the faulting which has occurred at various times in

the history of the region. Indeed, if the supposition is as correct as it appears to be that the ancestors of the Colorado River, several generations removed, had their courses originally determined by the configuration of the peneplain, it is evident that the peneplain must have embraced practically the entire area of the Colorado plateaus, and consequently this problem presents a very wide interest.

A comparison of the extent of erosion, taken in connection with the conditions under which it was accomplished, during the post-peneplain and canyon cycles furnishes added reason for separating them. The figures which follow are, of course, the roughest approximations, but they may serve to give some idea of the amount of material eroded. And first it may be noted that the period of the great denudation is distinctly in a class by itself. Taking Dutton's estimate of an average thickness of 10,000 feet of strata removed over an area of 13,000 square miles, the volume eroded is equal to 25,000 cubic miles; or a more conservative estimate, with the thickness of strata placed at 6,000 feet, is 16,000 cubic miles. The amounts of material eroded during the post-peneplain and canyon cycles were very much smaller; it is estimated that their combined volume is only about 5 to 10 per cent of that removed in the period of the great denudation.

The amount of material eroded during the post-peneplain cycle is placed at 800 cubic miles. This is based on the removal of an average thickness of 500 feet of Permian and Triassic strata from an area of some 8,000 square miles. The latter figure shows how widespread was the stripping of the soft strata overlying the resistant upper Aubrey limestone during this cycle. In view of so extensive a denudation ending, as it did, with the development of a mature topography of only slight relief, the conclusion seems justified that the region during this time must have stood at no great elevation above the sea.

The amount of material eroded during the canyon cycle is considered as equal to the volume of the various canyons of the region, which practically means the Grand Canyon and its tributaries, and in addition some volume of soft strata removed by stripping. This latter process has been confined to limited areas and the volume of material thus removed cannot well be calculated;

it is, therefore, arbitrarily placed at 50 cubic miles, which allows for the removal of over 100 feet of strata from an area of more than 2,000 square miles. Including this, the total volume of material eroded during the canyon cycle is placed at 600 cubic miles.

A contrast may thus be drawn between the removal of 800 cubic miles of Permian and Triassic strata over an area of some 8,000 square miles with the development of a mature topography on the stripped resistant limestone—the post-peneplain erosion—while the land stood at a fairly low elevation, and the erosion of 600 cubic miles of material as the result of canyon cutting—the canyon erosion—with the land at, or rising to, a high elevation. If it is asked whether the erosion above described occurred in a single cycle, the answer must be in the negative. For erosion in the canyon cycle has been proceeding at an extremely rapid rate and consequently the 600 cubic miles of material removed in the cutting of the youthful canyons indicates much too short a time to permit the stripping of the 800 cubic miles of Permian and Triassic strata from the surface of the plateau and the development of the mature topography on the underlying limestone. To consider the post-peneplain erosion as occurring in the same cycle as the canyon erosion is to include the greater within the lesser, thus producing an anomalous result. If, on the contrary, a thousand cubic miles of material had been eroded in the canyon cutting and but a few hundred stripped from the surface of the plateau, and especially if the mature topography had been developed on weak instead of resistant strata, it might be supposed to have entirely occurred in a single cycle. But in view of the evidence furnished by the mature valleys, the differences in direction between the mature and canyon systems of drainage, the relative amounts of erosion in the post-peneplain and canyon cycles, and the differences in the resistance of the strata eroded in the two periods, the conclusion is fully justified that the erosion of the post-peneplain and canyon cycles could not well have taken place in a single cycle and consequently the post-peneplain cycle must be given an independent rank.

An important consideration in separating the post-peneplain cycle of erosion from the preceding peneplain cycle and especially from the succeeding canyon cycle lies in the fact that the mature

topography of the intermediate cycle was developed on what was evidently, under the circumstances, a highly resistant formation, namely, the upper Aubrey cherty limestone. This formation is as resistant, for instance, as the basalt which was erupted after the development of the peneplain at the close of the period of the great denudation and is very much more resistant than the overlying Permian and Triassic strata remaining after the development of the peneplain. A comparison of the amount of erosion during the post-peneplain cycle in the extreme southwestern part of the plateau, where the limestone and basalt were present, and the remainder of the district which was covered, for the most part, with Permian and Triassic strata, is very instructive upon this point. The basalt in the former locality was only moderately dissected, and the limestone only slightly, as the result of erosion during the whole of the post-peneplain cycle, while elsewhere Permian and Triassic strata up to a maximum thickness of over 1,000 feet were removed. The difference suggests how erroneous might be an idea of the erosion based on incomplete observations. The point to be noted is that the development of a thoroughly mature topography, even of a low degree of relief and representing no great removal of material, on so resistant a formation as this limestone is indicative of an erosion interval as long in itself, perhaps, as that marked by the canyon cutting. And when to the time required for the development of the mature topography on the resistant limestone is added that necessary for the previous extensive and widespread removal of the overlying Permian and Triassic strata an interval is indicated which was probably much longer than that covered by the cutting of the youthful canyons. Moreover the strata involved in the latter process are not all so resistant as the upper Aubrey limestone on which the mature topography was developed. Several important formations are distinctly weaker, as, for example, much of the lower Aubrey red sandstone, and the presence of these weaker beds tends to increase the difference between the lengths of time required for the canyon cutting and post-peneplain erosion in favor of the latter. The interval covered by the post-peneplain cycle of erosion was very much shorter, of course, than that of the preceding period of the great denudation,

but, on the other hand, it certainly appears to have been much longer, taking the various factors into account, than the time required for the canyon cutting.

The evidence, therefore, indicates that the post-peneplain cycle of erosion should be clearly marked off from the preceding peneplain cycle and from the succeeding canyon cycle. The history of the region, as previously given, must be amended, consequently, by saying that after the close of the peneplain cycle of erosion, and the widespread eruption of basalt, another period of erosion began during which unprotected Permian and Triassic strata up to a thickness of 1,000 feet were removed from an area embracing the greater part of the Grand Canyon District. Where these strata were protected by the basalt their removal was incomplete and remnants now form the mesas and buttes, such as Mount Trumbull and Red Butte, which are found at various localities. It is also to be inferred from the widespread removal of these strata that the high cliffs bounding the region on the north and east experienced a further retreat. Davis says: ". . . . in the case of the Vermillion cliffs at Pipe Spring the retreat is likely, it seems to me, to have been several miles at least" (*b*, p. 37). After the removal of the Permian and Triassic strata erosion proceeded still farther and developed a mature topography of low relief in the underlying and resistant upper Aubrey cherty limestone and to a less extent in other formations. The revival of the forces of erosion is supposed to have been brought about by a slight elevation of the region above its stand at the close of the peneplain cycle. It is considered that the uplift was associated with a period of faulting, which has thus far not been specifically recognized. The movements of different periods have so often taken place along the same line of displacement in this region that detailed study is necessary in order to discriminate between them.[1]

[1] In a paper entitled "A Geological Excursion in the Grand Canyon District" (*Proc. Boston Soc. Nat. Hist.*, May, 1909) and published since the above was written, Dr. D. W. Johnson describes a third period of faulting on the Hurricane displacement in the vicinity of Toquerville, Utah. It occurred between the faulting of the plateau cycle—the first faulting of Huntington and Goldthwait—and that which introduced the canyon cycle of erosion, and amounted to about 1,000 feet. This appears to be the faulting which is here supposed to have immediately preceded the post-peneplain cycle of erosion.

The history of the Grand Canyon District, with the post-peneplain cycle of erosion introduced, may now be summarized as follows:

I. Period of folding and flexing.

II. Erosion cycle.

III. The first period of faulting. A period of extensive faulting.

IV. The peneplain cycle of erosion. This cycle closed with the widespread development of a peneplain. Relief produced by faulting (III) entirely obliterated. Widespread volcanic activity, marked by the eruption basalt, occurred shortly after the development of the peneplain and while the region still stood close to sea-level.

V. The second period of faulting. Faulting probably of less magnitude than that of the first and third periods.

VI. The post-peneplain cycle of erosion. Widespread stripping of Permian and Triassic strata and development of a mature topography on the underlying beds, principally the upper Aubrey limestone, at a horizon ranging from zero to 1,000 feet below the level of the peneplain. Further retreat of the high cliffs on the north and east sides of the district. Land stood at no great height above the sea.

VII. The third period of faulting, with broad regional uplift. Region raised from 4,000 to 6,000 feet above the position it occupied at the close of the post-peneplain cycle.

VIII. The canyon (present) cycle of erosion. Marked by the development of a canyon system of drainage of extreme youthfulness. Refreshing of cliff profiles. Erosion otherwise very slight.

The history above outlined is considerably more complex than that presented by Dutton and is believed to be complete so far as the principal events are concerned. It differs from previous interpretations in introducing the post-peneplain cycle of erosion, and it is felt that this cycle rests on evidence fully as conclusive as that which establishes the separate existence of the peneplain and canyon cycles of erosion. It removes the anomaly in the previous explanations of the widespread stripping of a very considerable thickness of Permian and Triassic strata and development of a mature topography on the resistant upper Aubrey limestone in the same cycle that has witnessed the cutting of the youthful canyons.

## POSITION OF EVENTS IN GEOLOGIC TIME

While the history of the Grand Canyon region, on the whole, possesses a very reasonable definiteness, the problem of placing the several events which comprise it in geologic time is quite unsatis-

factory, as there is no direct evidence to be derived from the district itself. The only method of attack is by correlation with the neighboring Basin Range country of Nevada, which in itself has not been studied in any great detail. Yet, notwithstanding the tentative nature of any conclusions that may be reached, it is desired to present the results of such a correlation, not only because they differ from those previously reached, but also because it is believed, in the light of known geologic events of recent date—especially in California—that they possess a very considerable suggestive value and may be useful to those who may later have occasion to study this general region.

The folding and flexing (I), as represented by the Kaibab and Echo Cliff monoclines, does not antedate the middle part of the Eocene, since the disturbance involves strata of Lower Eocene age in the high plateaus of Utah.[1] It seems probable, also, from other considerations, that it did not occur later than the end of the Eocene. The folding in the Grand Canyon District, to all appearances, is of the same age; it must be carefully distinguished, however, from certain broad warpings of much later date. Up to the present the folding and flexing movements have received much less study than the later faulting, although they are fully equal to the latter in importance, when their magnitude and extent, and the geographic changes involved are considered.

The correlation of greatest probability is that between the peneplain developed at the close of the peneplain cycle of erosion (IV), and the mature topography and local peneplains of the Basin Range country of southern Nevada and of Arizona. The point has not been so thoroughly studied as is desirable, but it seems clear to the writer, as the result of reconnaissance work, that there was originally a direct continuity between the maturely dissected Basin Ranges with local peneplains extending from their footslopes and the more distant highly developed peneplain of the present plateau region; they were the related parts of a single physiographic province. There is little doubt that this transition may be actually traced in Arizona, with only minor breaks, from the Bradshaw Mountains through the Black Hills on the west side of the

[1] Dutton, *op. cit.*, 74.

Verde Valley into the Black Mesa on its east side. At many points in the Black Hills and the mountains the remnants of the plain are capped by a basalt identical in character with that which covers the peneplain on the Black Mesa. Also the amount of erosion that has occurred since the basalt was erupted on the plain east of the Bradshaw Mountains compares very favorably with that of the post-peneplain cycle in the near-by present plateau region.[1] As both areas were situated in local drainage basins under similar climatic control and as the strata involved, judging from more recent results in the Grand Canyon of the Colorado, possessed approximately equal erodability, it may be concluded that the topography of the two areas was of contemporaneous origin.

The date at which the Basin Ranges originated as tilted block mountains possesses, therefore, a critical value, since it marks the time between which and the present the most clearly known events in the history of the Grand Canyon District occurred. This date is fixed by the age of certain formations—Pah-Ute of King and Siebert of Spurr—which were involved in the range-making movement. A Miocene age was originally assigned to these beds by King[2] and this has since been concurred in by Spurr,[3] Ball,[4] and Ransome.[5] The determination is not so positive as might be desired, nor is it certain that the entire Miocene is represented. In the absence of evidence to the contrary, however, it will be assumed that the sedimentary beds involved in the range-making do represent the whole of the Miocene. The probable correctness of this assumption is indicated by following consideration. If the strata involved in the mountain-making represented only the earlier part of the Miocene and the faulting which gave rise to the ranges as tilted block mountains occurred, for instance, in the middle of the Miocene, then the succeeding formation should be of late Miocene age, since the region during this time was a land area and the deposits were of a local nature. On the contrary, however, the next youngest formation is of Pliocene age; it rests unconformably on the older tilted strata of the ranges generally in a horizontal or

[1] H. H. Robinson, *op. cit.*, 120.

[2] *Explor. 40th Parallel*, I, 412–24.

[3] *U.S.G.S.*, XLII (1905), 66.

[4] *U.S.G.S.*, Bull. 308 (1907), 32.

[5] *U.S.G.S.*, LXVI (1909), 66.

but slightly disturbed position. On this basis, then, the Basin Ranges originated as tilted block mountains at the close of the Miocene.

It is to be noted that the relief produced by the extensive faulting, which followed in the present plateau region next after the Eocene folding, was entirely reduced in the development of the peneplain. A very considerable interval, therefore, must have intervened between the time of the faulting and the final degradation of the region to a peneplain. In view of the magnitude of the faulting and its time relation to the peneplain, it seems permissible to correlate it with that which gave rise to the Basin Ranges as tilted block mountains, and which likewise followed a period of folding.

After the faulting at the close of the Miocene the newly formed block mountains of the Basin Range region were attacked by erosive forces and reduced to mature forms. Contemporaneously local peneplains were developed, under favorable conditions, about the footslopes of the ranges,[1] while at greater distances—in the present plateau region—a highly developed peneplain covered thousands of square miles. There is at present no direct evidence to tell when this erosion cycle came to an end, so that it is necessary to make an assumption as to this date. It is the writer's opinion, based on the character and extent of the erosion in the several cycles through which the Grand Canyon region has passed, that the close of the peneplain cycle should be placed at the end of the Pliocene. This appears to be the most probable date when the volume of the erosion during the peneplain cycle and the widespread base-leveling are compared with the extent and nature of the erosion during the post-peneplain and canyon cycles. The point is one that is difficult to settle and may always remain, perhaps, a matter of individual judgment.

As the result of the foregoing assignment of dates, the post-peneplain and canyon cycles of erosion, with the pronounced faulting that came between them, are placed in the Quaternary. This is at variance with previous ideas. Dutton, for instance, spread the canyon cutting alone over both the Pliocene and Quaternary;[2] a previous correlation by the writer confined it to the

[1] Ball, *op. cit.*, 41. [2] *Ibid.*, chap. xii.

Quaternary,[1] while the present one throws it still farther forward into the latter part of that period. Granting the correctness of the assumptions previously made, the reasonableness of this conclusion seems evident when the relative amounts of erosion during the post-peneplain and canyon cycles, and the wide difference in the conditions under which it was accomplished are considered, although the correctness of the results in general remains for future demonstration. It is suggestive of the truth of the conclusion here reached, however, that Lee in his bulletin entitled "A Geological Reconnaissance of Western Arizona"[2] describes, at a number of localities, a thick unconsolidated gravelly formation that has experienced marked faulting. In speaking of this formation as it occurs in the Chemehuevis Valley, he says:

> The older gravels are horizontally bedded in some places but in others are faulted and highly inclined. . . . . In general appearance they resemble the Temple Bar Conglomerate and are provisionally correlated with it.[3]

The suggestive point is that the Temple Bar Conglomerate is considered as being of Quaternary age and deposited after a last period of pronounced faulting at the opening of the Quaternary, so that it should be comparatively undisturbed. If one may judge, however, from Lee's descriptions and cross-sections, the formation which he provisionally correlates with the Temple Bar Conglomerate has been very strongly faulted and tilted at a number of localities. This is easily explained, and Lee's correlation strengthened, if the major faulting which introduced the canyon cycle of erosion occurred during instead of at the beginning of the Quaternary. For with the faulting occurring during the middle or latter part of the Quaternary there would still have been ample time in the earlier part of that period for the deposition of heavy alluvial deposits upon the lowlands bordering the plateau country.

There are three other points which may receive further mention. One is that on the basis of the erosion cycles in the Grand Canyon district the mature topography of the Basin Ranges of southern Nevada and of Arizona should be considered as the result not only of the peneplain but also of the post-peneplain cycle of erosion. The former was much the more important, but the latter may have introduced significant modifications. Whether they would be

[1] *Ibid.*, 111. [2] *U.S.G.S.*, Bull. 352 (1908). [3] *Ibid.*, 43–44.

recognizable in the ranges themselves is questionable. Judging from the changes produced by erosion during the post-peneplain cycle in the plateau region, they should be most easily recognized about the footslopes of the ranges and in the peneplained areas.

A second point is that while the Basin Range country and plateau region, as they are known today, were probably to some extent differentiated at the close of the Miocene, the line of demarkation between the two regions was more or less obliterated, at some localities entirely, by the close of the peneplain cycle of erosion, which has been placed at the close of the Pliocene. At that time the Basin Range country in general constituted the uplands whose lowlands were situated, in part at least, in the present Grand Canyon District. At the close of the Pliocene the faulting appears to have been of such a nature that the two districts were again to some extent separated, but it was not until the pronounced faulting which introduced the canyon cycle of erosion that the Basin Range and Plateau provinces, as they are known today, were given, or began to be given, what has since developed into their maximum degree of demarkation.

It may also be noted, as a climatic incident in the history of the region, that a small glacier lived in the large interior valley of San Francisco Mountain, situated on the plateau south of the Grand Canyon, during the canyon cycle of erosion. An attempt has been made to calculate the temperature on the mountain at the time of the glaciation; the problem was approached by three different methods and the results showed reasonable agreements. Without going into the processes of calculation, which are reserved for a future paper, it may be said that the average result gave a temperature of 15° F. less than that of today. This result is in close agreement with determinations made elsewhere, and as it is a fair assumption that the region has experienced only slight changes in elevation since the glacier existed on the mountain, it may be taken as an approximate measure of the difference in temperature in this general region between what was certainly one of the latest and perhaps the last stage of the Glacial period and the present time. It is evident that if conditions were only sufficiently favorable for the existence of a small glacier on the mountain after the region had been elevated possibly as much as 5,000 feet at or

since the beginning of the canyon cycle of erosion they must have been very unfavorable for the existence of any glaciers during the post-peneplain cycle when the region stood nearer sea-level, unless the estimates of temperature during glacial time are much in error. It may be concluded, then, that San Francisco Mountain has experienced only the one period of glaciation which occurred in late Quaternary time.

The Tertiary history of the Grand Canyon District, with geologic dates assigned as given in the preceding pages, may be summarized in conclusion as follows:

I. Period of folding and flexing during the latter half or at the close of the Eocene.

II. Erosion period during the Miocene.

III. First period of faulting at close of the Miocene. A period of extensive faulting. It is correlated with the faulting that gave rise to the Basin Ranges of southern Nevada as tilted block mountains.

IV. The peneplain cycle of erosion during the Pliocene. The Miocene and Pliocene erosion, which are considered as constituting the latter and greater part of the Period of the Great Denudation, closed with the widespread development of a peneplain. This is correlated with the mature topography and local peneplains of the Basin Range country of southern Nevada and of Arizona. Relief produced by previous faulting (III) largely and at some localities entirely obliterated. Widespread volcanic activity, marked by the eruption of basalt, occurred shortly after the development of the peneplain and most probably while the region still stood close to sea-level.

V. The second period of faulting at the close of the Pliocene. Movements probably of less magnitude than those of the first and third periods.

VI. The post-peneplain cycle of erosion during the first part of the Quaternary. Widespread stripping of Permian and Triassic strata and development of a mature topography of low relief, principally on the upper Aubrey limestone, at a horizon ranging from zero to 1,000 feet below the level of the peneplain. Further retreat of the high cliffs on the north and east sides of the district. Land stood at no great height above the sea.

VII. The third period of faulting, with broad regional uplift, during the middle or latter part of the Quaternary. Region raised from 4,000 to 6,000 feet above the position it occupied at the close of the post-peneplain cycle of erosion.

VIII. The canyon cycle of erosion during the latter part of the Quaternary. Marked by the development of a canyon system of drainage of extreme youthfulness. Refreshing of cliff profiles. Erosion otherwise very slight. Colder atmospheric conditions prevailed during part of this cycle, at least, as indicated by the existence of a small glacier on San Francisco Mountain.